

SCALING FLAME LENGTHS OF LARGE DIFFUSION FLAMES

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The scaling laws for flame length of large buoyant diffusion flames have not been established on any basis except simple correlations and the correct parameters to be used in these have not been clearly established. Several possible parameters are discussed and a set of experiments is described in which the effects on the flame length of changing these parameters are investigated. The changes in the parameters are accomplished by diluting natural gas fuel with nitrogen and by heating and diluting the ambient air with products of combustion.

Variables and Parameters: The variables that control the flame height Z_f for large buoyancy controlled diffusion flames stabilized on circular burners with horizontal surfaces include: the acceleration of gravity, g ; the density, specific heat at constant pressure and specific heat ratios, and temperature of the ambient gas, ρ_∞ , C_{p_∞} , γ_∞ , and T_∞ ; and the corresponding values for the fuel at the source, subscript f , and the gas in the flame, subscript f . Other variables include: the total heat release rate of the fire, \dot{Q} , the loss from the fire due to radiation from soot, convective heat transfer to the burner, and etc., \dot{Q}_{loss} , and the net heating rate of the gas in the fire plume $\dot{Q}_c = (\dot{Q} - \dot{Q}_{loss})$ the heat added to the plume flow by the fire; the fuel velocity, U_f , at the surface of the burner or of a solid or liquid fuel; the chemical heat released by complete oxidation of the fuel per mass of fuel, ΔH_f , the stoichiometric fuel to air ratio, f_s , and the heat released per mass of air, $\Delta H_a = f_s \Delta H_f$. Here the heating value for the fuel ΔH_f is defined as the heat release when a kilogram of the fuel is completely oxidized to carbon dioxide and water vapor in standard air.

However, important factors concerning combustion processes in turbulent diffusion flames, such as the turbulence intensity, the rate of fuel consumption per unit volume of the flame or the production and combustion of soot, are ignored and the influence of the various density ratios have not been considered as separate parameters.

These variables can be arranged in a number of dimensionless parameters, and the changes produced in these parameters during the experiments are discussed in detail in the paper. The parameters include:

$$(Q^*) = \left(\frac{\dot{Q}}{\rho_\infty C_{p_\infty} T_\infty \sqrt{g D D^2}} \right), \quad H_f = \left(\frac{\Delta H_f}{C_{p_\infty} T_\infty} \right), \quad H_a = \left(\frac{f_s \Delta H_f}{C_{p_\infty} T_\infty} \right) \text{ and } X_L = \left(1 - \frac{\dot{Q}_c}{\dot{Q}} \right).$$

Experiments: Two sets of experiments were carried out. In the first, the parameters were changed by diluting a fixed flow rate of natural gas fuel with up to five moles of nitrogen per mole of fuel and the effects on the flame height were determined for a fixed flow rate of the natural gas fuel. In the second set of experiments, the flame was contained within a hood and the ambient gas was produced by recirculation of a mixture of air diluted with the products of combustion of the flame. This arrangement allowed the ambient gas temperature to be increased to 400° K and the oxygen mole fraction to decrease to 10% to 12% system. In both experiments, flame heights were determined using the methodology discussed in Cetegen et al (1984) where about 50 flame heights were measured. In a typical set of experiments, the fuel flow rate was held fixed while the dilution was increased from zero to the flammability limit.

In both experiments, the flame height was almost constant and increased less than 10% as the dilution was increased from zero to the flammability limit. In both experiments, the radiant flux from the fires was decreased smoothly from about 30% to about 10% of the chemical heat release; soot production was reduced to

almost zero near the flammability limit. Part of the observed 10% increase in flame height was a result of the increase in the heating rate of the plume due to this reduction in radiation heat loss as the dilution was increased.

In the second set of experiments, an increase in ambient gas temperature from 320° to 400° K had no systematic effect on flame height.

Conclusions: These results were compared with the predictions of the model of Steward (1972), and correlations of Cetegen et al (1982), Zukoski et al (1984) and Heskestad (1996). The results show that the \dot{Q}^* scaling proposed in Cetegen et al (1984) does a satisfactory job as a scaling parameter and suggests that \dot{Q}_c rather than \dot{Q} is the appropriate heat release parameter to use in \dot{Q}^* . Froude number scaling is certainly inappropriate here, and the model of Steward and correlation of Heskestad that depend on the heating value parameters, H_f and H_a , predicted much larger changes than were observed in the experiments.

In summary, \dot{Q}^* scaling, based on the convective heat release, is only weakly affected by either the dilution of the air or fuel, and is in reasonable agreement with the present results.

References

- Cetegen, B. M., Zukoski, E. E. and Kubota, T., (1984) "Entrainment in the Near and Far Field of Fire Plumes," *Comb. Sci. & Tech.*, 39, pp 305-331.
- Heskestad, Gunnar (1981) "Peak Velocities and Flame Heights of Buoyancy-Controlled Turbulent Diffusion Flames," *Eighteenth Sym. (Int.) on Comb.*, The Comb. Institute, pp 951-960.
- Steward, F. R. (1970) "Prediction of the Height of Turbulent Diffusion Flames," *Comb. Sci and Tech.*, 2, pp 203-212.
- Zukoski, E. E., Kubota, T. and Cetegen, B. (1984), "Visible Structure of Buoyant Diffusion Flames," *Twentieth Symp. (Int.) on Comb.*, The Comb. Institute, pp 361-366.

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